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RESEARCH

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ABSTRACT

In Brazilian sugarcane (*Saccharum* spp.) production systems, the practice of moving harvesting residue from row to inter-row positions (i.e., raking) has increased in response to producer concerns over the potential negative effects of sugarcane straw on crop establishment and stalk yield. Despite increasing adoption among sugarcane farmers, the impacts of straw raking practices on plant growth and yield remain unclear. A 2-yr experiment that included both dry and wet seasons was conducted at two sites in southeastern Brazil to evaluate straw management strategy effects on plant tillering, phytomass accumulation, plant nutritional status, and stalk yield. The experiments were established at the Bom Retiro mill and the Univalem mill. Experimental treatments included raking straw to inter-rows (raked), total straw removal (bare soil), and no straw removal (straw cover). Raked and bare soil treatments improved plant tillering but did not influence final plant population. Straw management had a slight effect on phytomass accumulation. Reduction of phytomass yield was observed from the first to the second ratoon during both seasons at both sites. At Bom Retiro, phytomass yield decreased 37% for stands established during the dry season and 19% for stands established during the wet season. At Univalem, phytomass yield decreased 20% for stands established during the dry season and 30% for stands established during the wet season. Retaining straw in the field (regardless of treatment) increased leaf tissue P content but not stalk yield. Raking straw from row to inter-row positions at these locations in southeastern Brazil had no benefit on sugarcane yield but may result in soil compaction and higher production costs over time.

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Abbreviations: DAH, days after harvesting; LAI, leaf area index.

Sugarcane (*Saccharum* spp.) harvesting in Brazil traditionally has involved burning leaf material prior to manually harvesting stalks. The practice of burning has increased public health and environmental concerns. Health concerns are due to increases in respiratory diseases attributed to air pollution (Cançado et al., 2006; Paraiso and Gouveia, 2015; Le Blond et al., 2017). Environmental concerns are associated with greater greenhouse gas emissions and poor working conditions associated with burning (Capaz et al., 2013; Galdos et al., 2013). Since the early 2000s, sugarcane harvesting has phased out burning and adopted mechanical harvesting to improve the sustainability of this production system (Pongpat et al., 2017; Bordonal et al., 2018a). This transition has required agronomic changes to manage the 10 to 20 Mg ha^{-1} of sugarcane residue remaining in the field after harvest (Hassuani et al., 2005; Walter et al., 2014; Carvalho et al., 2017).

Mechanical harvesting results in large amounts of straw being available for potential bioenergy production (Correa et al., 2017; Guerra et al., 2018). Using sugarcane straw as a feedstock for bioethanol (i.e., second-generation ethanol) production could

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help meet Brazil's fuel ethanol requirements, which are predicted to increase up to 200 billion L by 2021 (Goldemberg et al., 2014; Dodo et al., 2017; Lisboa et al., 2017).

Retaining a portion of sugarcane straw in the field is necessary for protecting several soil functions and to maintain or enhance soil quality (Carvalho et al., 2017; Cherubin et al., 2018). Residue retained on the soil surface creates a microenvironment that affects heat, water, and gas exchange between the soil and atmosphere (Cherubin et al., 2018). The straw blanket also affects several other soil functions and ecosystem services, including: reduction in evaporative water loss and thus an increase in soil moisture (Anjos et al., 2017); creating a beneficial environment for plants and soil biota (Carvalho et al., 2017; Cherubin et al., 2018) including sugarcane pests (Dinardo-Miranda and Fracasso, 2013); reduction in light intensity at the plant base (Toppa et al., 2010); a decrease in soil temperature (Correa et al., 2017); and improvement in soil structure (Castioni et al., 2018).

Agronomically, a straw blanket may negatively affect plant growth and stalk yield with the magnitude of this effect dependent on site-specific soil and climate conditions (Oliveira et al., 2001; Campos et al., 2010). Reducing incident light delays sprouting of basal vegetative buds (Toppa et al., 2010). Reducing soil temperature during the winter (Sandhu et al., 2013) and increasing soil moisture in early spring can limit plant growth and reduce stalk yield (Kingston et al., 2005; Viator et al., 2005; Viator and Wang, 2011). Sandhu et al. (2017) reported negative effects of a straw blanket on plant tillering and leaf area index (LAI) from 120 to 200 d but no effect on final stalk yield and sucrose concentrations under subtropical conditions. In Brazil, studies have shown slow initial crop growth and development in the presence of a straw blanket, especially in cooler areas of the main sugarcane-producing region (Oliveira et al., 2001; Campos et al., 2008; Campos et al., 2010; Landell et al., 2013).

In response to producer perceptions of potential undesirable effects of a straw blanket on sugarcane ratoons, most mills and farmers in southeastern Brazil have begun to move the straw blanket from the plant row to the interrows position using a tractor-mounted rake (Campos et al., 2008, 2010). Raking requires an additional machinery operation within each ratoon cycle potentially increasing soil compaction, which is already a critical problem in most Brazilian sugarcane fields (Souza et al., 2014; Cherubin et al., 2016; Bordonal et al., 2018a). Even though raking has been widely adopted within southeastern Brazil, the agronomic benefits of this management practice remain unclear (Carvalho et al., 2017). In a recent study conducted within the central-southern sugarcane producer region, Lisboa et al. (2018) reported small plant growth responses across the ratoon cycles between extreme straw-blanket management treatments (total vs. no straw removal). Thus, there are still uncertainties about the best management practices for postharvest residue.

Our hypothesis is that sugarcane's compensatory ability allows the crop to recover from potential negative effects caused by the straw blanket during the initial growth phases, resulting in no significant yield loss. Therefore, the raking operation is unnecessary to sustain crop yields for green harvested sugarcane fields in southeastern Brazil. This 2-yr experiment (conducted at two sites and during two harvesting seasons) aimed to quantify straw management effects on plant tillering, growth, plant nutrient status, and stalk yield.

MATERIALS AND METHODS

Study Sites

The experimental sites were located on sugarcane production farms in São Paulo State, near Capivari city at the Bom Retiro mill (22°59′42″ S, 47°30′34″ W) and near Valparaiso city at the Univalem mill (21°14′48″ S, 50°47′04″ W). Sites are referred to as Bom Retiro and Univalem hereafter. The locations chosen represent typical sugarcane-producing areas within southeastern Brazil, which accounts for >64% of the total production (Conab, 2019). The Bom Retiro climate is humid subtropical (Cwa, Köppen classification), characterized by dry winters and hot summers, with a mean annual temperature of 21.8°C and mean annual precipitation of 1289 mm. Precipitation and average daily temperature during the study period at the Bom Retiro site is presented in Fig. 1A. At Univalem, the climate is tropical (Aw, Köppen classification) and characterized by dry winters, with a mean annual temperature of 23.4°C and mean annual precipitation of 1241 mm. Precipitation and average daily temperature during the study period at the Univalem site is presented in Fig. 1B. Rainfall at both sites is concentrated in spring and summer (October–April), and the dry season occurs in autumn and winter (May–September). Climate information was provided by Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultur (CEPAGRI, http://www.cpa.unicamp.br) and Escola Superior de Agricultura Luiz de Queiróz (ESALQ, http://www.leb.esalq.usp.br/posto/).

Within each study site, experiments were conducted for 2 yr covering the first two ratoons (i.e., first and second) and two seasons (dry and wet). Sugarcane was planted in February 2013 at both sites. Dry-season straw treatments were established in winter after the first ratoon (cane plant) harvest in August 2014 and after the second ratoon harvest in August 2015, with final harvesting in August 2016. Wet-season straw experiments were established in spring at the time of harvesting in October 2014 and December 2015, with final harvesting in December 2016.

Sugarcane varieties CTC 14 and RB 867515 were cultivated in Bom Retiro and Univalem, respectively. CTC 14 has excellent ratoon longevity, is drought tolerant, and resistant to rust [*Puccinia kuehnii* (Kruger) E. Butler], scalding, yellowing, and to stalk borer (*Diatraea saccharalis* Fabricius) (Goes et al., 2011). RB 867515 exhibits optimum sprouting, especially if covered with a straw layer, is drought tolerant, and rarely sets seed (Marin, 2009). At both sites, sugarcane was planted using

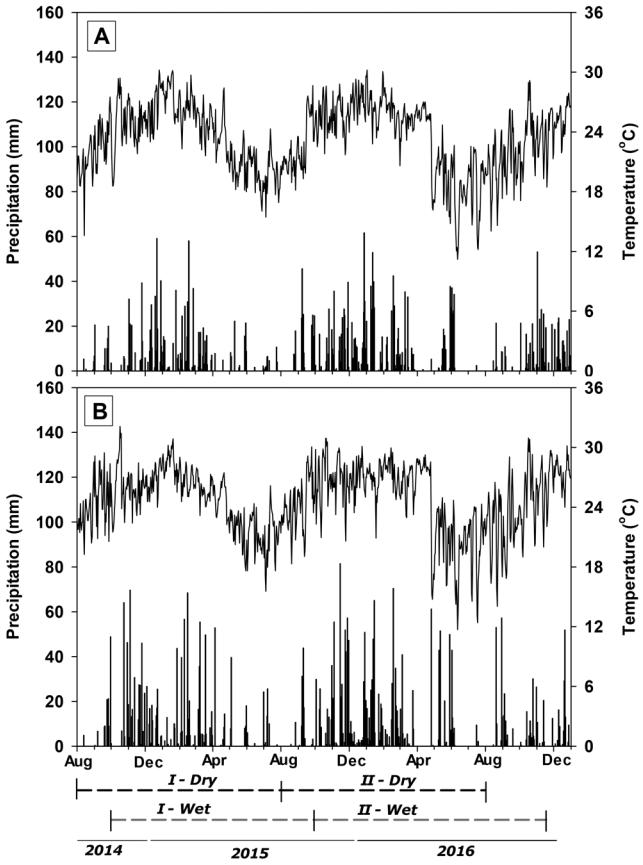

Fig. 1. Mean daily temperature (°C) and precipitation (mm) in (A) Bom Retiro and (B) Univalem. Black and green dashed lines indicate when treatments were applied in dry and wet seasons, respectively; I and II denote first and second ratoons.

an alternating double-row spacing of 1.5 and 0.9 m. Lime, gypsum, and fertilizer for the first and second ratoons were applied according to Raij et al. (1997).

Experimental Design

The experimental design consisted of three treatments (bare soil, straw cover, and rake), applied in a randomized block design, with four replications. Each plot was ~50 × 25 m. The raked treatment was imposed 4 d after sugarcane harvest by moving the straw to the inter-rows using a tractor mounted rake (DMB Máquinas e Implementos Agrícolas) (Fig. 2).

To remove all straw from the soil surface for the bare soil treatment, the sugarcane harvester was set up with both extractor (i.e., primary and secondary) fans turned off so that the straw was collected along with chopped stalks in the wagons. Details regarding harvester setup and efficiency of mechanical straw removal procedures are described in Lisboa et al. (2017). Fallen leaves (i.e., senesced leaves) associated with each ratoon cycle were not removed because they were not mechanically deposited by the harvester. Sugarcane straw retention amounts, by treatment and year, are presented in Table 1.

Soil samples (one per plot) for the 0- to 10-, 10- to 20-, and 20- to 30-cm depth increments were collected and characterized for soil texture and chemical attributes at the beginning of each experiment (Table 2). Total organic C and total N contents were determined by dry combustion using an elemental analyzer (furnace at 1350°C in pure O_2) (Leco CN-2000). The P, K, Ca, and Mg concentrations were determined by the ion exchange resin method. Phosphorus was quantified colorimetrically, Ca and Mg were quantified using atomic absorption spectrophotometry, and K by flame atomic-emission spectroscopy (Raij et al., 2001).

Soon after treatment establishment, a composite sample of sugarcane straw (one per plot) was collected and analyzed to determine C and macronutrient concentrations (Table 3). Total C and N within the plant tissue were determined by dry combustion using an elemental analyzer. Phosphorus, K, Ca, Mg, and S concentrations in plant tissue were quantified according to Malavolta et al. (1997).

Sugarcane Growth and Yield Measurements

Plant growth responses to straw management were evaluated using the following parameters: tillering, phytomass accumulation, and LAI. Measurement days for all vegetative metrics occurred during each year and each season at a time when sugarcane growth stages were similar. As a result, timing of measurements often did not correspond to the exact same dates between sites, years, or seasons because plant growth stage varied with specific growth conditions (time of year, weather conditions, etc.).

Tillering was determined by counting the number of new shoots within a 20-m segment of each plot. Each evaluation was made at the same place throughout both ratoon cycles. Dry-season tiller counts at both sites were made 60, 90, 120, and

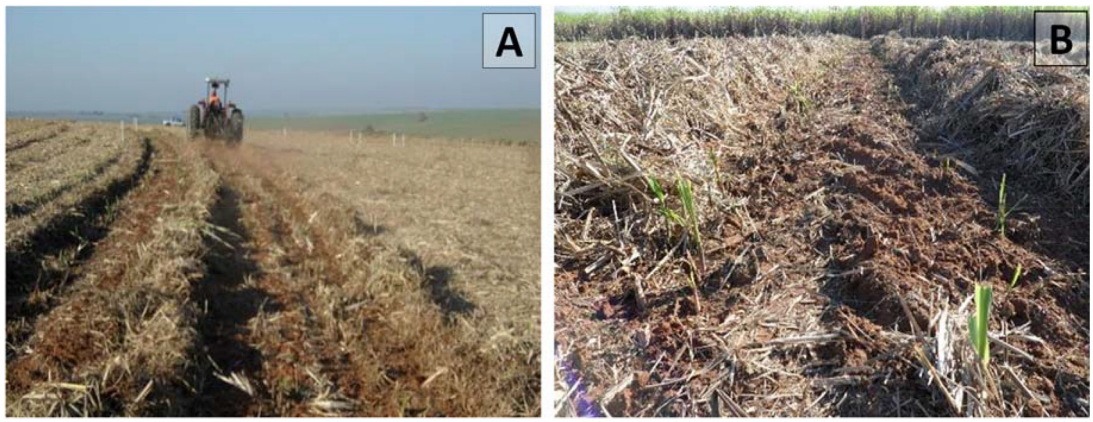

Fig. 2. (A) Sugarcane straw being moved to inter-row positions after harvesting; (B) straw piled in the inter-rows, showing crop tillers sprouting after raking.

210 d after harvesting (DAH) during the first year. Wet-season counts were made 60, 90, and 135 DAH. In the second year, dry-season tiller counts were made at 30, 60, 90, 120, and 360 DAH, whereas wet-season counts were at 30, 60, 90, 120, 180, and 360 DAH.

Phytomass accumulation throughout each ratoon cycle was determined using destructive sampling of all aboveground biomass within a 4-m crop row segment. Biomass yield evaluations prior to the fifth month of each ratoon were determined by weighing all of the fresh phytomass on an electronic scale (maximum capacity = 40 kg). Biomass was then ground with a forage grinder, and a representative subsample was collected for analysis. After the fifth month of each ratoon cycle, the plant phytomass was separated into three components: dry leaves, green leaves, and stalks. Fresh weight for each component was determined before grinding, subsampling, and determining dry weight by oven drying at 65°C until constant mass. Total phytomass yield per hectare (Mg ha^{-1}) was calculated using a 1.2-m row spacing with 8333 m of row per hectare.

During the first year at Bom Retiro, biomass evaluations were made at 120, 210, 290, and 360 DAH in the dry season and at 90, 135, 230, and 370 DAH during the wet season. At Univalem, measurements were made at 120, 210, 270, and 360 DAH during the dry season and at 90, 135, 230, and 410 DAH during the wet season. In the second year, biomass evaluations were made at 180 and 360 DAH in the wet-season treatments and at 210 and 360 d in the dry-season treatments at both sites.

The LAI was measured at 15 randomly chosen points within the eight central rows of each plot. Each reading was made 0.6 m from the ground surface using a LAI-2200 plant canopy analyzer (Li-Cor). In the first year, LAI was measured at 170 and 210 DAH within the dry-season experiments, and at 90 and 135 DAH in the wet-season studies. In the second year, LAI was measured at 90 and 120 DAH for both seasons and sites.

Stalk yield was quantified at the end of each annual growth cycle by mechanically harvesting the five central rows (500 m long) and collecting the material in a wagon equipped with a scale. After weighing, the fresh mass was extrapolated to megagrams per hectare.

Second Ratoon Sugarcane Nutrient Status

Plant nutrient concentrations were measured only during the second growing season (i.e., second ratoon) after the straw treatments had an opportunity to influence nutrient availability. Plant samples were collected at two times to evaluate any changes within ratoon cycle: early in the second ratoon, and late

Table 1. Sugarcane straw retained on the soil surface by management practice.

	Straw mechanically retained							
	Bom Retiro mill				Univalem mill			
	Dry season		Wet season		Dry season		Wet season	
Sugarcane straw management	Year I	Year II	Year I	Year II	Year I	Year II	Year I	Year II
	Mg ha^{-1}†							
Bare soil‡	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Straw cover	16.6	14.7	18.9	13.6	15.0	12.4	16.4	13.7
Rake	15.6	17.2	23.3	14.3	13.8	12.1	13.2	13.3

† Dry mass.

‡ Plus senesced leaves (not measured).

Table 2. Soil characterization (0–30 cm) at Bom Retiro and Univalem.

Location	Depth	pH_{water}	C	P	K	Ca	Mg	BS†	AS†	Clay	Silt	Sand
	cm		g kg^{-1}	mg dm^{-3}	mmol$_c$ dm^{-3}			%		g kg^{-1}		
Bom Retiro	0–10	5.2	11.3	29.3	9.3	26.1	7.7	68.8	0.8	330	60	610
	10–20	4.8	11.0	24.9	5.1	19.0	5.9	54.7	3.5	330	70	600
	20–30	4.5	9.4	22.1	3.3	12.5	2.95	36.8	4.2	335	65	600
Univalem	0–10	5.2	6.1	17.4	3.3	9.3	2.9	51.1	2.4	112	23	865
	10–20	4.8	5.5	14.1	2.6	4.8	1.5	34.8	5.6	113	22	865
	20–30	4.5	4.9	12.7	2.1	3.6	1.0	27.5	7.4	120	20	860

† BS, base saturation; AS, aluminum saturation. Adapted from Satiro et al. (2017).

Table 3. Sugarcane straw C and macronutrient contents (N, P, K, Ca, Mg, and S) for Bom Retiro and Univalem sites.

Sites†	C	N	P	K	Ca	Mg	S	C/N
	g kg^{-1}							
Bom Retiro$^{(I-\ dry)}$	437	3.68	0.36	2.23	2.83	1.71	0.93	119
Bom Retiro$^{(I-\ wet)}$	467	4.02	0.38	2.45	2.44	1.54	0.74	116
Bom Retiro$^{(II-\ dry)}$	470	4.80	0.79	6.12	4.99	1.31	1.62	98
Bom Retiro$^{(II-\ wet)}$	422	6.04	0.58	1.30	8.55	2.55	0.95	73
Univalem$^{(I-\ dry)}$	475	3.22	0.37	2.26	2.34	2.10	0.50	147
Univalem$^{(I-\ wet)}$	479	2.58	0.39	1.66	1.96	1.38	0.45	177
Univalem$^{(II-\ dry)}$	479	3.57	0.54	1.35	4.22	1.08	0.71	134
Univalem$^{(II-\ wet)}$	470	3.10	0.34	0.56	2.44	1.24	0.35	152

† $^{(I)}$ and $^{(II)}$ denote the first and second sugarcane ratoon, respectively.

in the second ratoon. The early ratoon plant sampling occurred ~4 mo after the first harvest. At the early ratoon sampling, fully expanded leaves (i.e., visible dewlap) from the third node were collected to evaluate plant nutrient status (Raij et al., 1997). Within each plot, 50 leaves were randomly collected, dried, ground, and analyzed to determine N, P, K, Ca, Mg, and S concentrations in the tissue. Leaves were separated in thirds. The middle third (without the midrib) was oven dried at 65°C before grinding for analysis. Late ratoon sampling occurred 6 (wet-season treatments) or 7 mo (dry-season treatments) after the first harvest. At the late ratoon sampling, whole plants were collected, separated into components (i.e., dry leaves, green leaves, and stalk), and prepared for N, P, K, Ca, Mg, and S analysis. Each plant component was ground in a forage grinder, subsampled, and oven dried at 65°C. Plant tissue macronutrient concentrations were determined for both sampling periods according to Malavolta et al. (1997). For reporting, plant tissue N, P, and K concentrations from the first sampling event are referred to as N1, P1, and K1, and those from the second evaluation are named N2, P2, and K2, respectively.

Stalk Composition and Quality

Before mechanically harvesting each plot, 10 plants were chosen at random and harvested by hand. Several composition and quality parameters (i.e., fiber content [fiber], apparent sucrose in the juice [Pol], soluble solids content [Brix], apparent juice purity [purity], and reducing sugars [RS]) were analyzed using procedures adopted Consecana (2006).

Our primary goal was to determine effects of different straw blanket management treatments on plant tillering, phytomass accumulation, plant nutritional status, and stalk yield. However, to expand our database, sugarcane composition and quality were also evaluated.

Statistical Analysis

First, a nonlinear regression model (Eq. [1]) was fitted to plant growth data (phytomass accumulation) as a function of DAH. Individual curves were developed for each straw management treatment for each year. All models were written and fitted using the *nls* (nonlinear least square) function available within R Software (R Core Team, 2016).

$$Y = \frac{Y_{max}}{1 + e^{-\frac{(DAH - A)}{B}}} \quad [1]$$

where Y is the phytomass yield (Mg ha^{-1}; i.e., the response variable), Y_{max} is the maximum phytomass yield (Mg ha^{-1}) for each ratoon cycle, A is the inflection point at which the growth rate is maximized, and B controls the steepness of the curve. The parameters Y_{max} and B were used as agronomic indicators to evaluate the impact of the treatments on the phytomass yield performance. Details about each parameter of the Sigmoid function are described in Archontoulis and Miguez (2015).

Second, for measurement date within each site (DAH) and season, a one-way ANOVA was performed to test the effect of straw management (bare soil, straw cover, and rake) on plant responses (e.g., plant tillering, LAI, and stalk yield). We applied the ANOVA considering the three treatments within each time (i.e., at each DAH in which the observations occurred), since our aim was not to include time for these plant indicators group. When treatments were significant (F test $p < 0.05$), treatment means were compared using Tukey's test ($p < 0.05$). Comparisons of means were performed using the *agricolae* R package (Mendiburu and Simon, 2015) available within R Software (R Core Team, 2016).

Finally, canonical discriminant analysis was performed on second ratoon plant nutrient data to identify whether early (NPK1) vs. late (NPK2) plant nutrient status would separate into straw management groups along independent canonical axes (i.e., canonical variables). Biplot graphs were created using the first two canonical axes values. Canonical variable means for each treatment were compared by 95% confidence ellipses. When confidence ellipses overlapped, mean differences were considered nonsignificant. Canonical discriminant analyses were performed using the *candisc* R package, available within R Software (R Core Team, 2016).

RESULTS AND DISCUSSION

Plant Tillering Response to Straw Management

Straw treatments had season-specific and site-specific effects on plant tillering (Fig. 3). In general, tillering tended to be highest in the bare soil treatment, with tillering more sensitive to straw management earlier in the growing season and more sensitive at the Bom Retiro site than at the Univalem site. One possible reason for this response was that Univalem experienced higher temperatures than Bom Retiro, especially early in each ratoon cycle (Supplemental Fig. S1). The higher temperatures may have minimized the expected suppression of tillering by the straw blanket during both wet seasons (Fig. 3G and 3H). In addition, given that leaf emergence is dependent on temperature (Sinclair et al., 2004), warmer conditions at Univalem may have accelerated plant development and resulted in faster canopy closure, which also decreased straw management effects on LAI at Univalem (Supplemental Fig. S2E–S2H).

The presence of the sugarcane straw blanket on the soil surface was expected to suppress plant tillering by lowering soil temperatures (Viator et al., 2005; Toppa et al., 2010; Sandhu et al., 2013; Awe et al., 2015; Correa et al., 2017) and acting as a physical barrier to tillering. Previous studies, however, have shown variable plant tillering responses to straw cover. Nxumalo et al. (2017) reported that delayed plant emergence and early crop establishment due to straw cover did not affect the final plant population compared with straw removal. In contrast, Campos et al. (2010) concluded that raking improved plant tillering and final population compared with no raking (i.e., straw cover), particularly for cooler regions of southeastern Brazil. Our results were similar to those of Campos et al. (2010), especially at the cooler Bom Retiro site, where the plant tillering responses were similar between bare soil

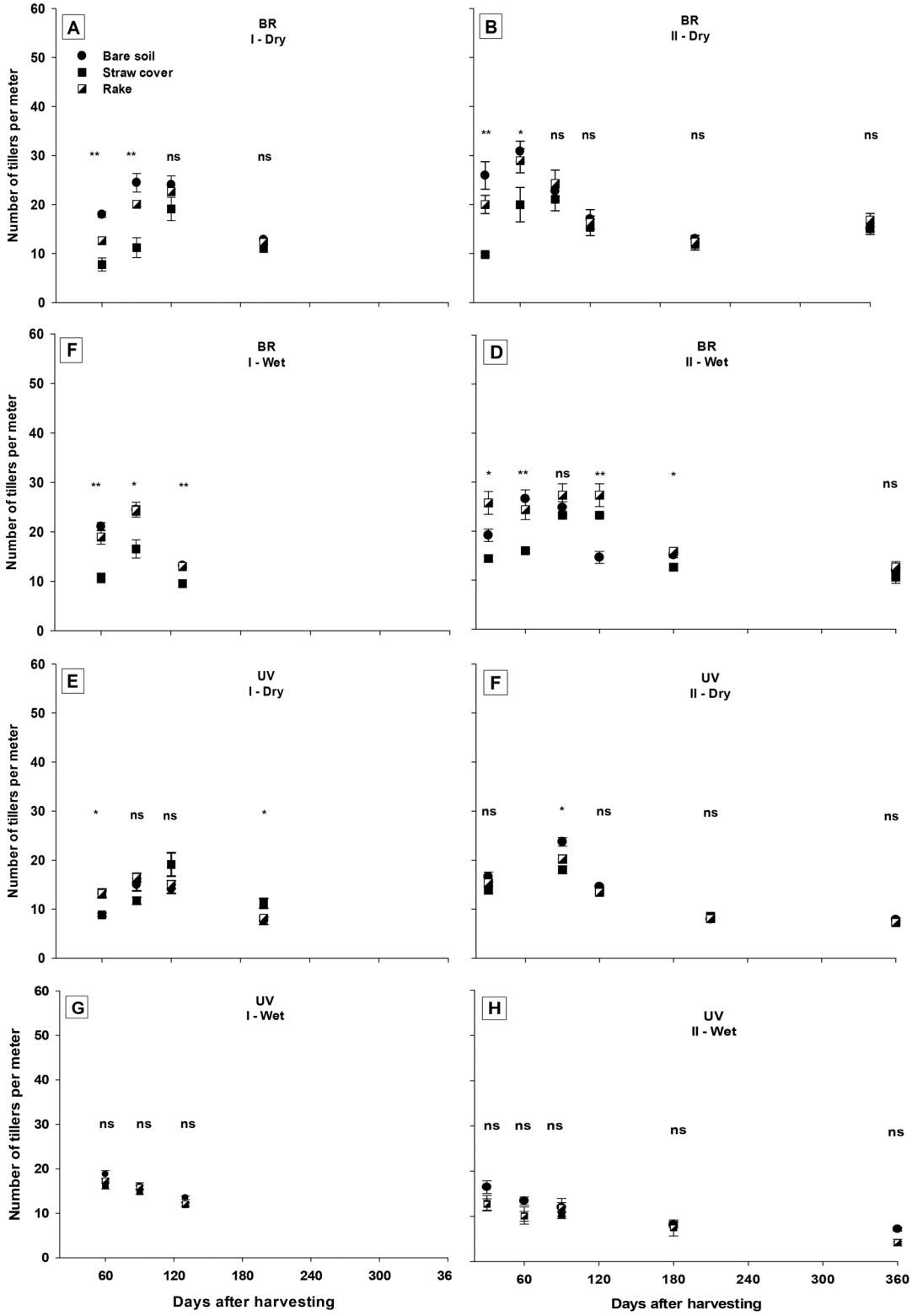

Fig. 3. Sugarcane tillering dynamics under different straw blanket management treatments established during the dry- and wet-season experiments at the Bom Retiro (BR, A–D) and Univalem (UV, E–H) and conducted over two ratoons (I and II). ** and * denote that means differ significantly according to Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns, nonsignificant; error bars denote SEM.

and raking treatments. However, straw cover treatments did not decrease the final plant population at the end of the ratoon cycle in our study (Fig. 3).

Overall, effects of straw cover on sugarcane tiller development and final plant population are unclear and variable depending primarily on the amount of straw and ratoon cycle (Aquino et al., 2017; Lisboa et al., 2018). In Bandeirantes, Paraná (i.e., southern Brazil), final plant population was significantly affected by straw amounts ranging from 0 to 20 Mg ha^{-1} in the first ratoon, but there

was no verifiable negative effect in the second ratoon (Aquino et al., 2017). However, Tavares et al. (2010) reported that tiller number and final plant population were enhanced at the beginning and end of crop cycles conducted over 16 yr in Linhares, Espírito Santo , which is located in southeastern Brazil. These locations are colder and warmer, respectively, than the sites where our study was performed.

Reduced rainfall volume from December 2015 to April 2016 at Bom Retiro (Supplemental Fig. S1A) and from December 2014 to January 2015 at Univalem (Supplemental Fig. S1B) may explain the inversion in plant tillering patterns for the different straw management treatments. For instance, decreased rainfall and consequently low soil moisture reduced tiller production for the bare soil treatment in the wet-season experiment during the second ratoon at Bom Retiro (Fig. 3D). Those same conditions may have favored a reduction in the number of tillers for bare soil and rake treatments in the dry-season experiment at Univalem during the fourth and seventh months of the first ratoon (Fig. 3E). On the other hand, straw cover (i.e., the maintenance of straw on soil surface) probably conserved soil water (Anjos et al., 2017; Correa et al., 2017) and positively affected tiller number for both experiments during those time periods.

Phytomass Response to Straw Management

Phytomass accumulation during each ratoon was fitted using sigmoidal models as a function of DAH (Fig. 4), as previously reported in the literature (Leite et al., 2016; Mariano et al., 2016; Lisboa et al., 2018). Overall, phytomass yield for each ratoon cycle and season occurred in three phases. The initial lag phase was characterized by slow phytomass accumulation, followed by a linear phase of rapid phytomass accumulation, then ending with a stationary phase characterized by low accumulation. The duration of each phase is shown in Supplemental Table S2. Over all ratoons, harvest seasons, and straw treatments, the average length for the lag, linear, and stationary phases was 123, 82, and 155 d, respectively. Phytomass accumulation during those phases averaged 19, 75, and 6%, respectively.

Phytomass yield at Bom Retiro was higher than at Univalem (∼48 and 23%, respectively, for dry and wet seasons during the first ratoon, and ∼34% higher for both seasons during the second ratoon). This reflected more favorable soils for crop production at Bom Retiro (Table 2), as discussed by Satiro et al. (2017). Comparisons between the first and second ratoons at both sites show that phytomass yield at Bom Retiro was ∼37 and 19% lower for all treatments during dry and wet seasons, respectively, whereas at Univalem, they were ∼20 and 30% lower, respectively. Decreases in crop yield with successive ratoons are well documented for sugarcane (Singh et al., 2012; Lisboa et al., 2018). Each ratoon requires at least three machinery operations: fertilization, weed control, and harvesting. In most fields where straw is not removed along with the stalk, raking adds an additional machinery operation. Greater machinery use could lead to higher risk of soil compaction (Souza et al., 2014; Cherubin et al., 2016; Bordonal et al., 2018a), which reduces root growth (Souza et al., 2014) and limits soil rooting volume for obtaining nutrients and water (Singh et al., 2012). Heavy machine traffic also can damage root systems and create plant gaps (i.e., reductions in plant population) (Lisboa et al., 2018). Thus, with each subsequent ratoon cycle, phytomass yield decreases indirectly from compaction and directly from stand damage. Despite the fact of raking straw blanket to the inter-row position leads to increased tiller numbers (Fig. 3A and 3E), as previously reported by Campos et al. (2008, 2010), this straw blanket management did not favor phytomass accumulation in our study.

Second Ratoon Plant Nutrient Status

Straw management effects on second ratoon plant nutrient status were largely limited to the Univalem site during the wet season (Table 4). For both early and late ratoon plants, N, P, and K (and S, to a lesser extent) contents in all tissues tended to be lowest in the bare soil treatment and highest in the rake treatment, with intermediate values in the straw cover treatment. Although Univalem plant P in the dry season was ∼15 and 11% higher for the straw cover and raking treatments, respectively, than for bare soil management, these differences increased to ∼20 and 27%, respectively, in the wet season. Univalem plant nutrient status was more responsive to straw treatments than Bom Retiro, presumably because the low fertility of coarse-textured soils at Univalem made plants more sensitive to residue-derived nutrient inputs (Satiro et al., 2017).

Discriminant analysis of early and late plant nutrient status during the second ratoon cycle showed that straw management treatments could be identified to some extent at all sites in all harvest seasons. At Bom Retiro, Canonical Variable 1 explained ∼98 and 92% of the data variance for experiments conducted within dry (Fig. 5A) and wet (Fig. 5B) seasons, with better separation between straw management occurring during the dry season. In contrast with no statistical differences in straw treatments using ANOVA (Table 4), nonparametric discriminant analysis did reveal that plant nutrient status was correlated with straw management at Bom Retiro.

At the Univalem site, Canonical Variable 1 also explained ∼92 and 93% of the variation among straw managements treatments established during the dry (Fig. 5C) and wet (Fig. 5D) seasons. At this site, straw cover significantly increased N, P, and K concentrations in the plant tissue and the amount of N and P removed in green leaves during the fourth and sixth months of the dry season. In contrast, bare soil and rake treatments

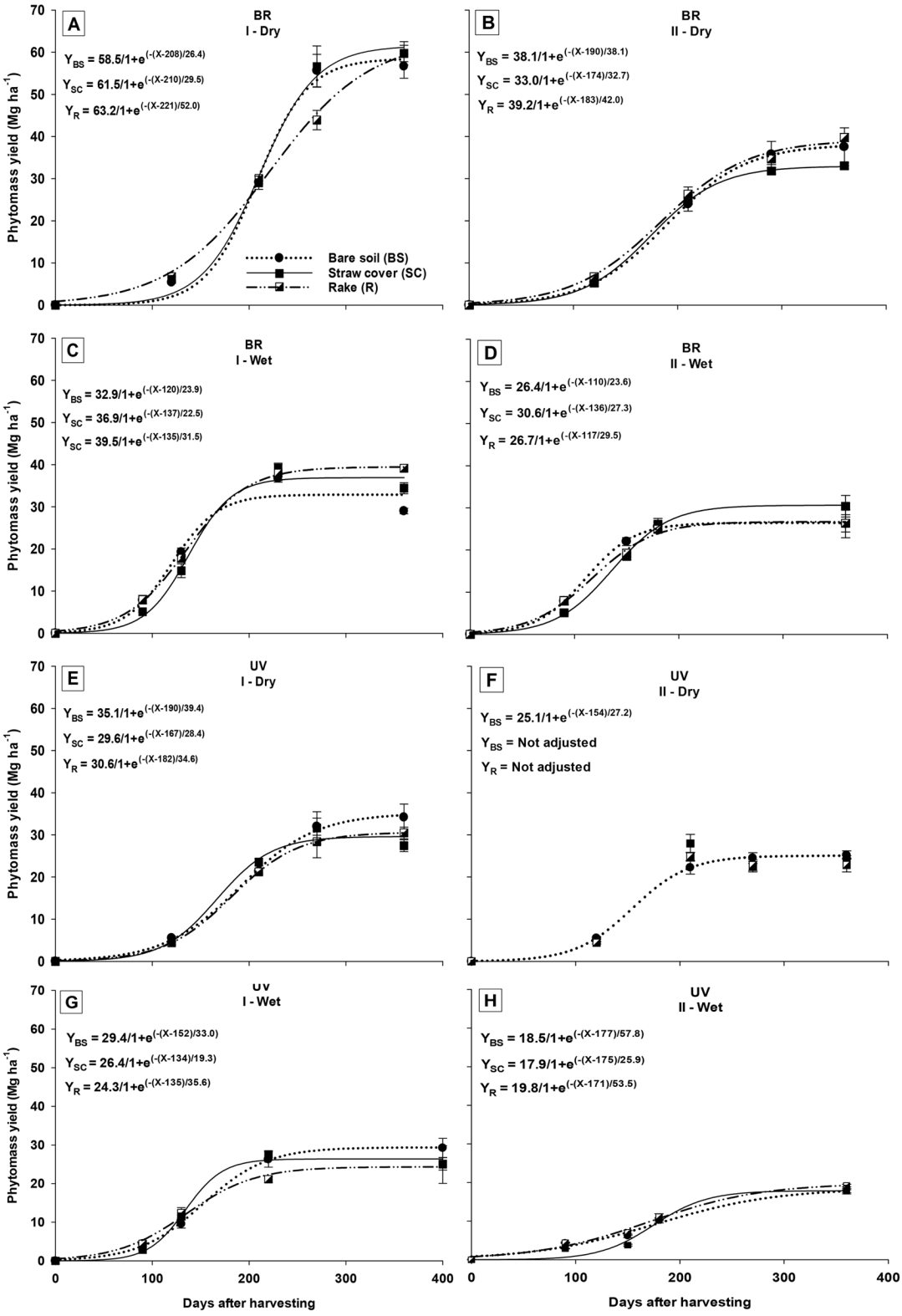

Fig. 4. Phytomass accumulation curves of sugarcane cultivated under different straw blanket management treatments in experiments established during the dry and wet season at Bom Retiro (BR, A–D) and Univalem (UV, E–H) and conducted over the first (I) and second (II) ratoons. Phytomass accumulation curves were derived from Eq. [1]. $Y_{BS,}$ bare soil; Y_{SC}, straw cover; and Y_R, ranking.

had minimal effect on the amount of K removed by green leaves (Fig. 5C). Straw cover and raking treatments were correlated with N, P, and K content in both the fourth and sixth months of the wet season (Fig. 5D). Bare soil management during this time was negatively correlated with N, P, and K content in plant tissue, as well as the amount of these elements within the green leaves in the fourth and sixth months. This response was similar to that observed during the dry season at Univalem (Fig. 5C).

Table 4. Second ratoon plant nutrient concentrations in sugarcane under different straw management treatments at both sites and seasons

Nutrient content	Bom Retiro mill								Univalem mill							
	Dry season				Wet season				Dry season				Wet season			
	Bare soil	Straw cover	Rake	Mean	Bare soil	Straw cover	Rake	Mean	Bare soil	Straw cover	Rake	Mean	Bare soil	Straw cover	Rake	Mean
	Early ratoon nutrient status (4 mo)															
	g kg^{-1}															
N	23.6	24.3	24.2	24.0	12.6	13.0	12.3	12.6	14.6	15.3	14.4	14.8	21.2	21.1	25.5	22.6
P	2.3	2.5	2.4	2.4	1.1	2.1	2.1	2.0	1.8b†	2.1a	2.0ab	2.0	1.6b	2.0ab	2.2a	1.9
K	9.4	11.0	9.9	10.1	9.9	8.9	9.8	9.5	7.1	18.1	7.6	10.9	8.0	9.9	9.4	9.1
Ca	3.3	4.1	3.4	3.6	3.4	3.8	3.3	3.5	3.2	3.8	4.1	3.7	3.6	3.6	3.4	3.5
Mg	1.5	1.4	1.4	1.4	1.6	1.2	1.4	1.4	1.1	1.3	1.4	1.2	1.6	2.1	1.9	1.9
S	1.5	1.7	1.6	1.6	2.3	2.4	2.4	2.4	0.7	0.8	0.7	0.2	1.9c	2.2b	2.7a	2.2
	Late ratoon nutrient status (6–7 mo)															
	kg ha^{-1}															
	Dry leaves															
N	22.4	30.8	28.0	27.1	20.9	19.4	20.1	20.1	6.8	10.9	7.7	8.5	6.4b	12.3a	11.5a	10.1
P	0.53	0.95	0.90	0.8	0.59	0.64	0.64	0.8	0.9	1.2	1.0	1.0	0.9b	2.0ab	2.2a	1.7
K	11.1	24.0	21.5	18.9	16.7	16.7	12.2	15.2	8.7	10.7	9.6	9.7	6.7	6.3	7.0	6.7
Ca	26.9	33.1	29.1	29.7	27.4	29.1	28.9	28.5	21.9	24.6	20.5	22.3	10.6	15.7	15.2	13.8
Mg	7.8	11.9	10.4	10.1	8.3	7.4	7.5	7.7	6.0	8.7	7.2	7.3	3.3	3.8	5.3	4.1
S	8.5	9.6	9.0	9.0	5.7	5.8	4.6	5.4	4.6	4.3	4.6	4.5	2.0	2.6	2.6	2.4
	Green leaves															
N	51.4	45.7	52.2	49.8	66.3	72.1	64.8	67.7	11.4	13.3	13.4	12.7	12.7	14.4	16.5	14.5
P	5.1	6.8	6.4	6.1	6.9	9.0	7.6	7.9	1.9	1.9	2.0	1.9	2.5	2.7	3.1	2.8
K	60.0	59.0	52.6	57.2	82.7	100	88.7	90.4	16.1	14.5	15.1	15.2	16.2b	22.0ab	24.5a	20.9
Ca	13.3	12.5	13.4	13.1	26.0	25.9	24.4	25.5	3.8	4.1	4.5	4.1	3.6	3.3	3.5	3.5
Mg	8.1	6.0	6.0	6.7	9.5	9.7	10.4	9.9	1.9	2.1	2.2	2.1	1.8	2.1	2.4	2.13
S	8.4	9.5	10.1	9.3	12.6	15.1	13.2	13.7	1.7	1.9	1.8	1.8	1.6	1.6	1.7	1.6
	Stalks															
N	77.5	66.3	70.2	71.3	56.8	53.2	50.0	53.3	17.9	20.9	16.4	18.4	14.9	13.3	15.1	14.5
P	6.4b	12.8a	6.0b	8.4	6.6	8.9	7.4	7.6	6.2	8.1	8.5	7.6	2.9b	4.2ab	5.5a	4.2
K	155.3	151.0	143.9	150.1	78.3	110.1	94.3	94.2	26.7	28.9	33.2	29.6	6.1b	24.6a	26.1a	18.9
Ca	28.1	24.7	24.0	25.6	14.6	14.3	13.8	14.2	8.0	8.2	7.6	7.9	2.4	2.7	3.0	2.7
Mg	29.1	21.0	23.2	24.4	12.9	13.8	15.9	14.2	6.2	6.3	6.4	6.3	2.0	2.6	3.0	2.6
S	36.1	40.3	36.2	37.5	25.3	24.8	21.9	24.0	7.9b	7.6b	11.4a	8.9	2.0	2.0	2.3	2.1

† Within each harvesting season × straw × plant tissue treatment, means followed by different letters are significantly different (Tukey, $p < 0.05$).

In general, both treatments that retained straw (i.e., straw cover, raked) enhanced N and P concentrations in the plant tissue both early and late in the second ratoon. Increased plant nutrient concentrations may reflect the benefits of retaining straw, such as enhanced nutrient cycling (Sousa Jr. et al., 2018) and/or increased C accumulation (Galdos et al., 2017; Cherubin et al., 2018; Sousa Jr. et al., 2018), water storage and infiltration (Valim et al., 2016; Anjos et al., 2017), and biological activity (Paredes Jr. et al., 2015). Healthy soils generally have increased availability of N and P for plant uptake, which subsequently increases plant tissue concentrations of these elements when straw is retained. Because sugarcane cultivation is performed across a wide range of soil textural classes in Brazil (Manzatto et al., 2009; Satiro et al., 2017) and raking reduces soil cover, additional studies are needed to determine how this practice affects soil conservation and subsequently the quality of contrasting soil types. In fields where straw is removed completely for bioenergy production (i.e., second generation and bioelectricity), special attention is required, since the straw has an essential role in various soil functions, such as preventing soil physical degradation (Satiro et al., 2017; Castioni et al., 2018), increasing C content (Bordonal et al., 2018b), and nutrient cycling (Fortes et al., 2012; Almeida et al., 2015).

Stalk Yield

Sugarcane straw management did not affect stalk yield for either season, ratoon, or site (Fig. 6). Averaged over 2 yr, maintenance of straw on the soil surface reduced stalk yield at Univalem in the wet season only (Fig. 6D). Stalk yield was not affected by raking when compared with straw covered soil ($p = 0.466$).

Although previous studies have shown short-term benefits of straw retention on surface soil chemical and physical attributes (Satiro et al., 2017; Sousa Jr. et al., 2018;

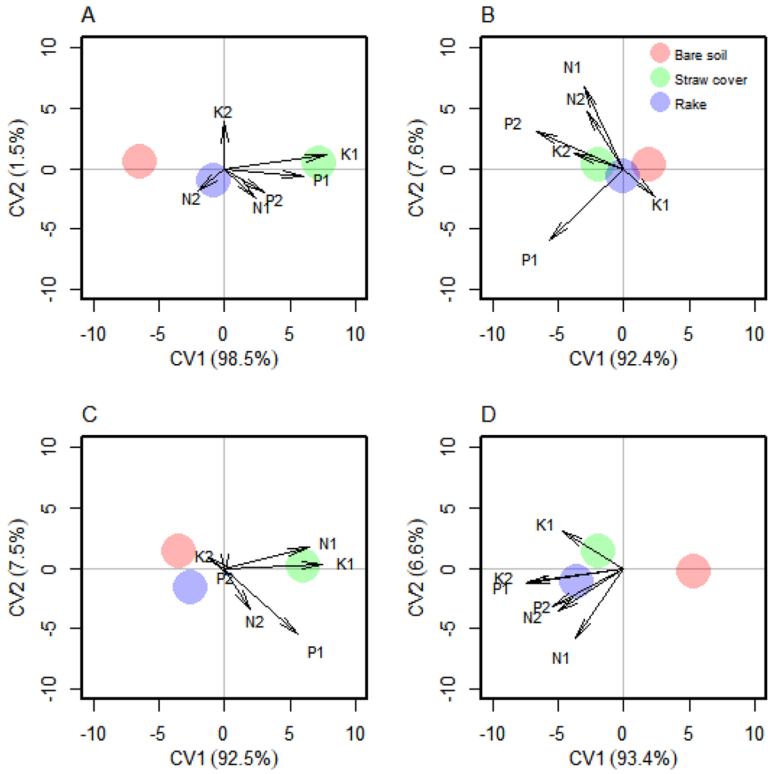

Fig. 5. Effect of the straw management on plant nutritional status within the experiments performed during the (A) dry and (B) wet season at Bom Retiro, whereas Plots C and D represent the same correlation in dry and wet seasons at Univalem. Colored dots represent confidences ellipses (95%) for the means of the scores of the two first canonical variables (CVs) in a biplot representation; arrows denote how the means of the CVs are affected by original variables in each management. N, P, and K followed by 1 and 2 are respectively the plant tissue content of these elements at 120 and 210 d after harvesting.

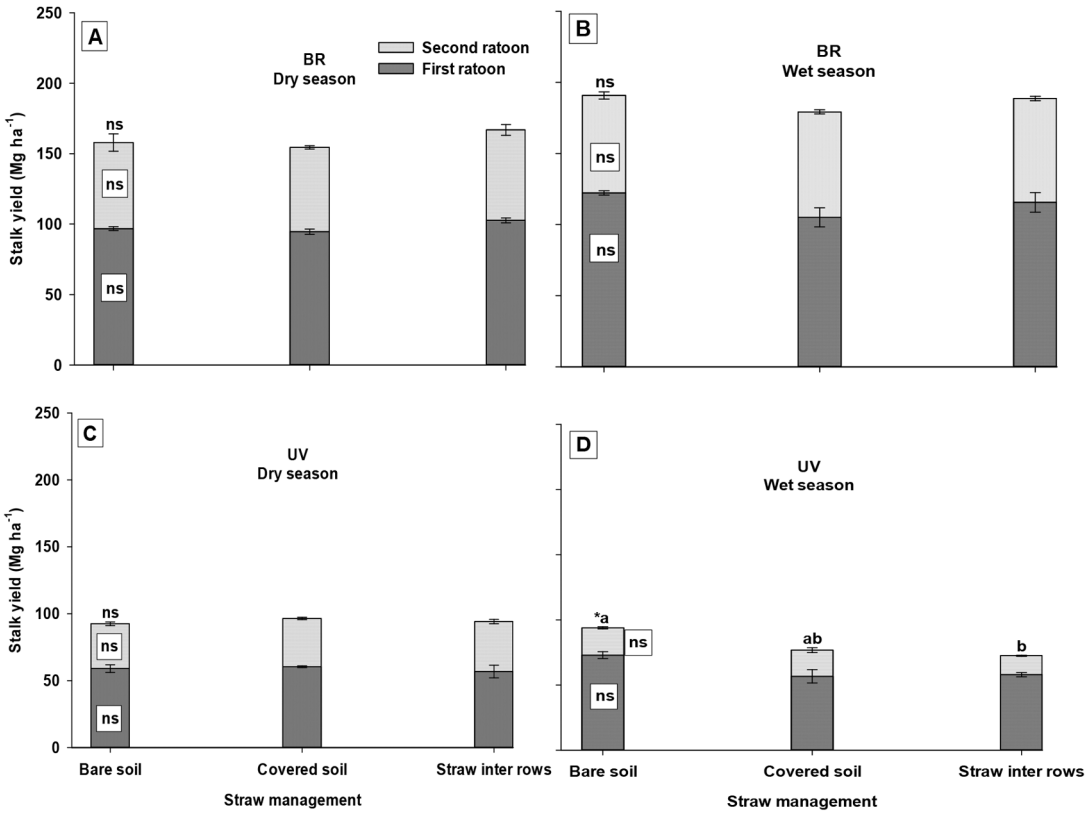

Fig. 6. Stalk yield of sugarcane cultivated under different straw blanket managements treatments established during the dry and wet season at Bom Retiro (BR, A and B) and Univalem (UV, C and D) over two ratoons; * significant by Tukey's test ($p < 0.05$); ns, nonsignificant; error bars denote SEM.

Lisboa et al., 2019), neither plant growth nor stalk yield were affected by straw management (Lisboa et al., 2018). Because the long-term impacts of straw management on sugarcane production are unknown, longer term studies (Aquino et al., 2018) are essential for understanding whether and how straw management affects plant growth and stalk yield over time.

Overall, the benefits of straw management (i.e., raking) appear more important for sugarcane growth and stalk yield under wet and cold conditions in the subtropical regions where the crop has <1 yr to complete a growing season. Under these climatic conditions, straw retention delays plant tillering in the winter and early spring, shortening plant exposure to more suitable conditions for phytomass accumulation over the growing cycle (Viator et al., 2005). In contrast, for tropical conditions where ratoon cycles are longer and temperatures higher, complete straw retention (i.e., without raking) did not affect plant tillering and development (Bordonal et al., 2018b).

Stalk Quality

Straw management did not affect any parameters associated with industrial sugarcane quality in either season. However, stalks from the wet-season experiments presented lower quality than those harvested during the dry season (for further details, see the supplemental discussion).

CONCLUSIONS

Managing sugarcane straw by raking, which is widely used in southeastern Brazil, enhanced sprouting but did not affect phytomass accumulation, final plant population, or yield, regardless of soil and climate conditions. Overall, plant nutrient status was slightly affected by straw blanket management, where plant nutrient concentrations tended to decrease with straw removal. Plant P concentrations were especially sensitive to straw retention under poorer soil fertility, suggesting that removal of straw in lower fertility soils could alter fertilizer strategies in systems that utilize straw removal.

Based on this short-term study, we found no evidence that raking improved yields or stalk quality and therefore conclude that raking is an unnecessary practice in southeastern Brazil. The absence of straw management effect on sugarcane yield or stalk quality, however, suggests that moderate removal of sugarcane straw could provide a feasible feedstock for bioenergy demand, but the benefits of retaining residue for the soil–plant system should not be disregarded.

Supplemental Material

Supplemental material is available online for this article.

Conflict of Interest

The authors declare that there is no conflict of interest.

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